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NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20034

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HOT FORMING, HEAT TREATING, AND MECHANICAL EVALUATION OF 4-INCH-THICK Ti-6Al-4V, ELI PLATE

by

Frank J. Lengenfelder

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MATERIALS DEPARTMENT

Annapolis

RESEARCH AND DEVELOPMENT REPORT

August 1972

Report 28-269

Hot Forming, Heat Treating, and Mechanical Evaluation of 4-Inch-Thick Ti-6Al-4V, ELI Plate

Report 28-269

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Naval Ship Research and Development Center
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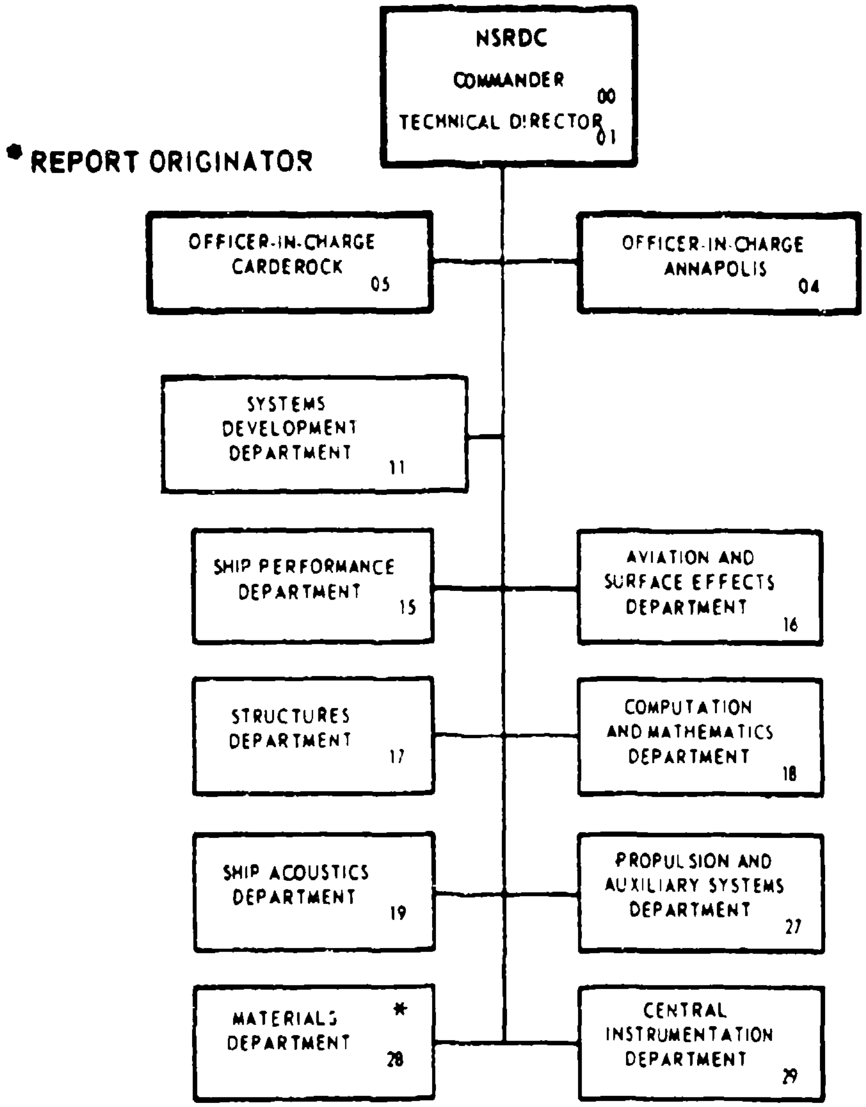

DEPARTMENT OF THE NAVY

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

BETHESDA, MD. 20034

HOT FORMING, HEAT TREATING, AND MECHANICAL EVALUATION OF 4-INCH-THICK Ti-6A1-4V, ELI PLATE

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ABSTRACT

Elevated temperature tensile properties of the Ti-6Al-4V, ELI grade alloy were determined and a forming temperature range was selected. A 7-foot-diameter hemisphere was hot-press formed from a 4-inch-thick plate according to laboratory-developed parameters. Mechanical property tests were conducted on the plate material before and after hot forming and after heat treating of the formed material. Results of these tests showed a lower tensile yield strength after hot forming and restoration of this property after heat treatment. The results indicate that a tensile yield strength of 120,000 pounds per square inch can be obtained throughout the thickness of the formed hemisphere after appropriate heat treatment.

ADMINISTRATIVE INFORMATION

Plate material was procured and the hemisphere was formed under Task Area S4607-001, Task 11896, Deep Submergence Systems Program (reference (a)). Material testing and heat treatment was performed under Work Unit 1-2822-101-00, Task Area SF 54-541-005, Task 12392. This report completes the work on milestone 7 of reference (b).

ADMINISTRATIVE REFERENCES

(a) NAVAPLSCIENLAB Program Summary S4607-001, Task 11896 of 1 Nov 1968

(b) NAVSHIPRANDCEN Annapolis Program Summary SF 54-541-005, Work Unit 2822-101 of 1 May 1972.

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INTRODUCTION

An investigation to develop information necessary for fabrication of heavy-section thicknesses of alloy titanium in the 100/120 ksi* yield strength range for use in hull structures is being conducted as outlined in reference (b). This work is in support of a Naval Ship Systems Command research and development program to develop and evaluate titanium alloys for use as a structural material in deep diving submersibles.

BACKGROUND

Forming studies have been conducted on near-alpha titanium alloys having tensile yield strengths on the low end of the 100/120 ksi range. Forgings up to 5 inches thick and hot-press-formed hemispheres 7 feet in diameter and 3 inches thick have been produced with these alloys and their mechanical properties, in these forms, have been determined. Heavy-section forgings of alpha-beta titanium alloys having tensile yield strengths at the high end of the 100/120 ksi range have been produced and their properties have also been determined and reported.[1]

SCOPE

The work covered by this report extends the state of art for hot forming, heavy-section, alpha-beta alloy titanium (Ti-6Al-4V, ELI) plate. It also shows the effects of hot forming and heat treatment on the mechanical properties of this alloy in 4-inch thicknesses.

MATERIAL

Material for this work was obtained from the largest round-rolled plate produced in any titanium alloy. The plate, shown on the mill in figure 1, finished to 4 inches thick by 160 inches in diameter. The alloy was the extra low interstitial (below 1000 ppm** oxygen content) modification of the alpha-beta Ti-6Al-4V alloy. This modification to the standard alloy results in higher toughness without substantial reduction in strength. Producer certified mechanical properties and chemical composition are shown in table 1.

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*ksi - thousand pounds per square inch.

[1] Superscripts refer to similarly numbered entries in the Technical References at the end of the text.

**Abbreviations used in this text are from the GPO Style Manual, 1967, unless otherwise noted.

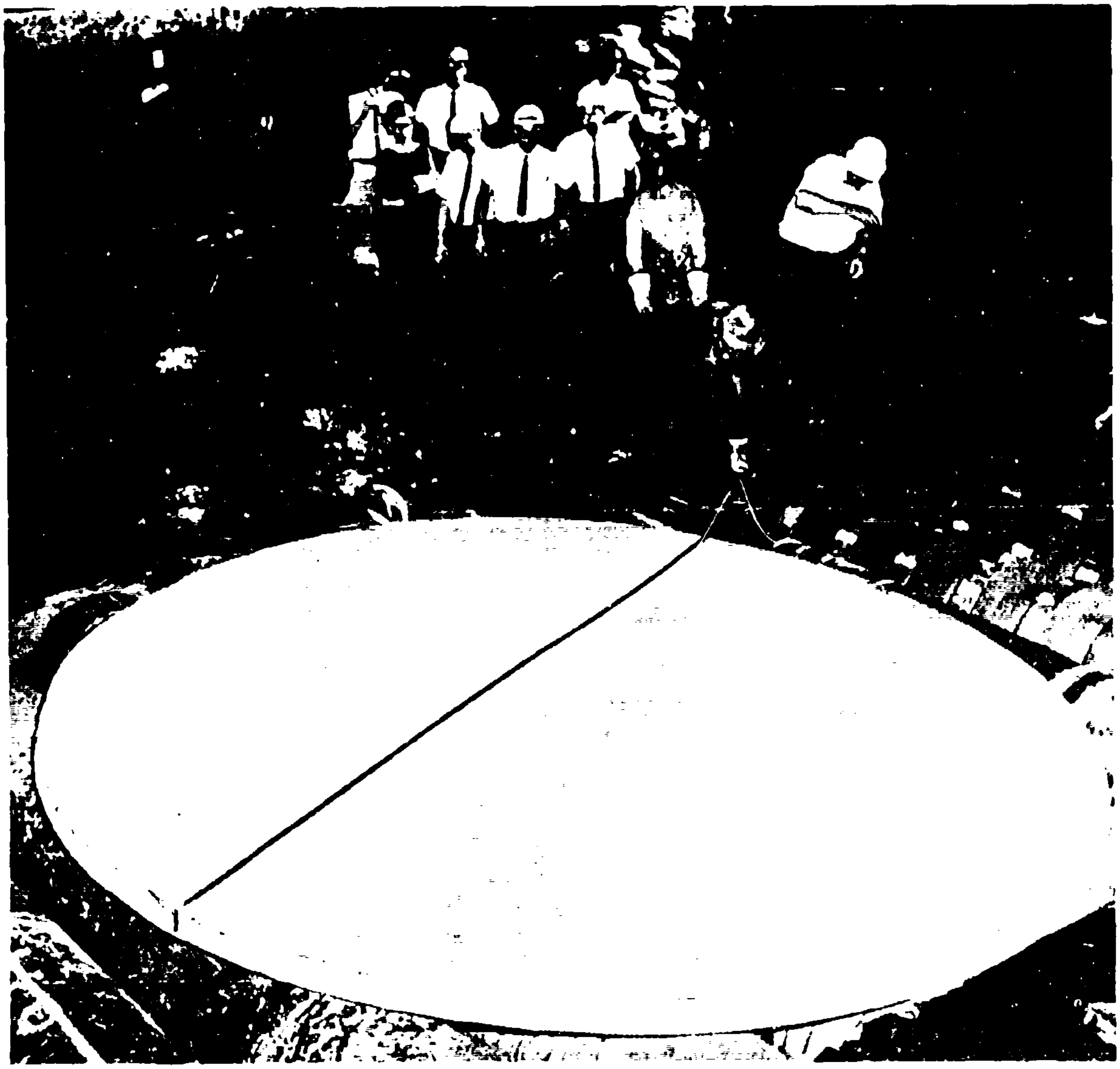


Figure 1
Four-Inch-Thick, 160-Inch-Diameter Plate of Ti-6Al-4V, ELI, Alloy on Rolling Mill

TABLE 1

PRODUCERS CERTIFIED MECHANICAL PROPERTIES AND CHEMICAL COMPOSITION

Chemistry, %: Ingot (Average of Top, Center, Bottom)

C	-	0.025
N	-	0.007
Fe	-	0.075
Al	-	6.3
V	-	4.4
O	-	0.090 } Final Product
H, ppm	-	73 } Final Product
Ti	-	remainder

Tensile Properties	Short Transverse	Transverse	Short Transverse	Transverse
Ultimate, ksi	124.0	126.0	127.0	129.0
Yield, ksi (0.2% Offset)	109.0	113.0	116.0	117.0
Elongation, % (inches)	10.0	9.0	10.0	13.0
Reduction in Area, %	30.0	32.0	30.0	30.0

Impact, Room Temperature, ft-lb	-	21.5
Weight, lb	-	13,000
Size, inches	-	4.0 thick 160 diameter
Test Forge Procedure	-	Production annealed at 1350° F for 1 hour, furnace cooled to 1000° F, then air cooled

The following pertinent facts about the plate production should be noted:

- The 13,000-pound plate was produced from a single heat with approximately an 80% efficiency from ingot to product.

- Initial breakdown of the billet was accomplished by forging parallel to the longitudinal axis to produce an 18-inch-thick-disk.

- Rolling temperatures were above the beta transus for initial passes, but the reheat furnace temperature was maintained below the beta transus for finishing passes on the plate.

- The exact temperature/reduction schedule is proprietery to the producer and, although a laboratory representative observed the plate rolling operations, details were not made available for report purposes.

PROCEDURE

Tension, compression, and Charpy V-notch specimens were taken from the periphery of the round-rolled plate at two locations 90 degrees apart. At each location, specimens were oriented to be either radial or tangential and were taken at six levels in the thickness. These specimens were used to establish the baseplate mechanical properties.

Additional tension specimens were prepared for use in establishing hot-forming parameters. Elevated temperature tensile tests were conducted in a vacuum furnace at 50° F intervals from 1250° to 1700° F. From the results of these tests, a hot-press-forming temperature range was chosen.

A 120-inch-diameter disk was flame cut from the remaining plate and shipped to the Lukens Steel Company, Coatesville, Pa., for hot-press forming. Forming was accomplished under the direction of a naval laboratory metallurgist. The plate was heated to 1800° F and was formed, in two stages, into a 7-foot-diameter hemisphere. One reheat was used between the forming steps and all forming was accomplished within the temperature range previously established by elevated temperature tests at this laboratory. The hemisphere was air-cooled from the forming temperature without subsequent heat treatment.

Figure 2 shows the hemisphere and an area from which a dropout was flame cut. On the advice of NAVSEC (SEC 6101D), the dropout area was selected to coincide with the location of an ALVIN vehicle viewpoint in the event that this hemisphere might find use as a hull section in a similar vehicle. Material from this dropout was used to prepare tension, compression, and Charpy V-notch specimens from layers in the thickness and in the same orientation as the specimens taken from the as-received plate.

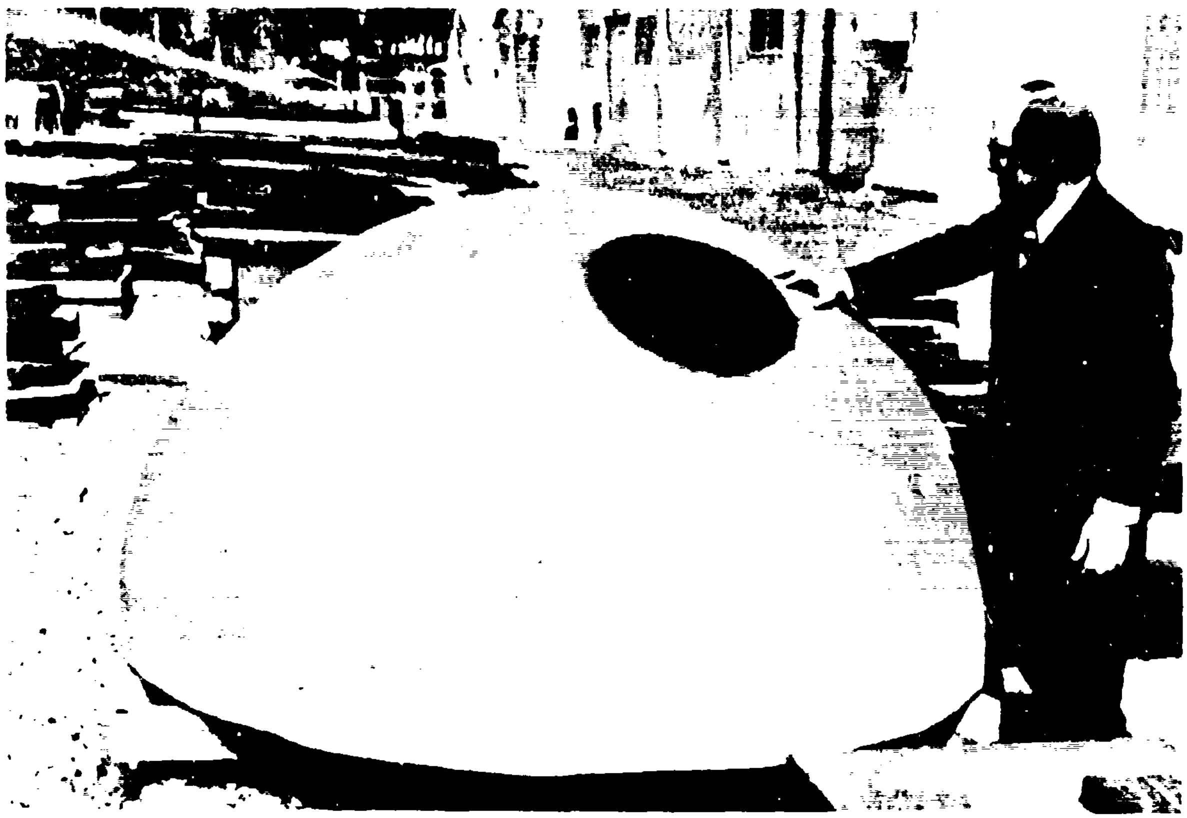


Figure 2
Hot-Press-Formed, 7-Foot-Diameter, Ti-6Al-4V, ELI, Alloy Hemisphere

Six-inch-square blocks, taken from the dropout material, were heat treated to determine the highest strength toughness combination which could be developed through a 4-inch-thick section. The literature was reviewed and heat treatments were selected which were likely to give the highest strength and toughness and which were practical for application to a 7-foot-diameter hemisphere. The four treatments used were as follows:

- Solution treat at 1550° F, water quench; age at 900° F.
- Solution treat at 1750° F, water quench; age at 900° F.
- Solution treat at 1750° F, spray water quench; age at 900° F.
- Solution treat at 1750° F, 1-minute delay then spray water quench; age at 900° F.

Specimens for mechanical property tests were prepared from layers in the thickness similar to those taken from the untreated hemisphere dropout and as-received plate but in a radial direction only.

RESULTS AND DISCUSSION

Elevated temperature tensile properties are presented in table 2 and are shown graphically in figure 3. Specimens tested at 1300° F and above could not be tested to fracture since physical limitations of the equipment did not permit the extensions to which these specimens were capable. Elongation and reduction in area values for these temperatures are presented for information only and are considered to be far below the actual values. Tensile specimens tested at 1750° and 1550° F are shown in items (a) and (b), figure 4, respectively. Item (a), figure 4 shows deformation over the entire gauge length by movement of individual grains while item (b), figure 4 shows good ductility with material deforming in aggregate. From this and the data of table 2 and figure 3, the press forming range for this alloy was placed at 1500° to 1750° F. Below 1500° F, strength increases substantially and the risk of surface cracking at cold spots becomes high. Pressing at temperatures above 1750° F may result in "orange peel" surfaces and unstable plastic deformation. Since large grains form at temperatures above the beta transus and relatively little working of the material to reduce the grain size occurs during hot pressing, it was considered desirable to limit the maximum temperature for heating and reheating of the blank and partly formed hemisphere to 1800° F.

Hot-press forming of the 7-foot-diameter, 4-inch-thick hemisphere was performed in two stages since the total height of the formed hemisphere and the dies exceeded the opening capacity of the largest press available. The engineers at Lukens Steel Company designed a die setup which could be changed during pressing and thereby extended the rated press capacity. The first stage of the pressing was accomplished without unusual difficulty considering the size of plate being worked. Problems in handling caused a delay in moving the partly formed hemisphere from the reheat furnace to the press. In the final pressing stage, temperature of the hemisphere dropped to within 50° F of the minimum set by laboratory tests. The forming forces required because of this low temperature approached the maximum press load capability and caused eight 1 1/4-inch-diameter die hold-down bars to fracture.

Although forming was satisfactorily completed before the breakdown, it is believed that hot-press forming of larger, high-strength alloy titanium hemispheres is not feasible on presently available equipment.

TABLE 2

ELEVATED TEMPERATURE TENSILE PROPERTIES

Temperature °F	Ultimate Tensile Strength ksi	Tensile Yield Strength 0.2% Offset ksi	Elongation in 4D (1) %	Reduction In Area (1) %
1250	44.0	37.2	51.4	83.0
1300	29.6	25.9	54.0	90.0
1350	26.4	22.2	(2)	93.0
1400	19.7 (3)	15.2 (3)	73.0	96.0
1450	18.0	14.2	(2)	94.0
1500	16.7	12.1	82.0	95.0
1550	10.0	8.6	(2)	91.0
1600	7.6	6.4	90.0	94.0
1650	5.2	4.0	(2)	93.0
1700	3.0	2.6	112.0	91.0

(1) Elongation and reduction in area values are the highest recorded for specimens tested at and above 1300° F; they did not break.

(2) Value not recorded.

(3) Strength values for this temperature are average of four specimens; values at other temperatures are average of two specimens.

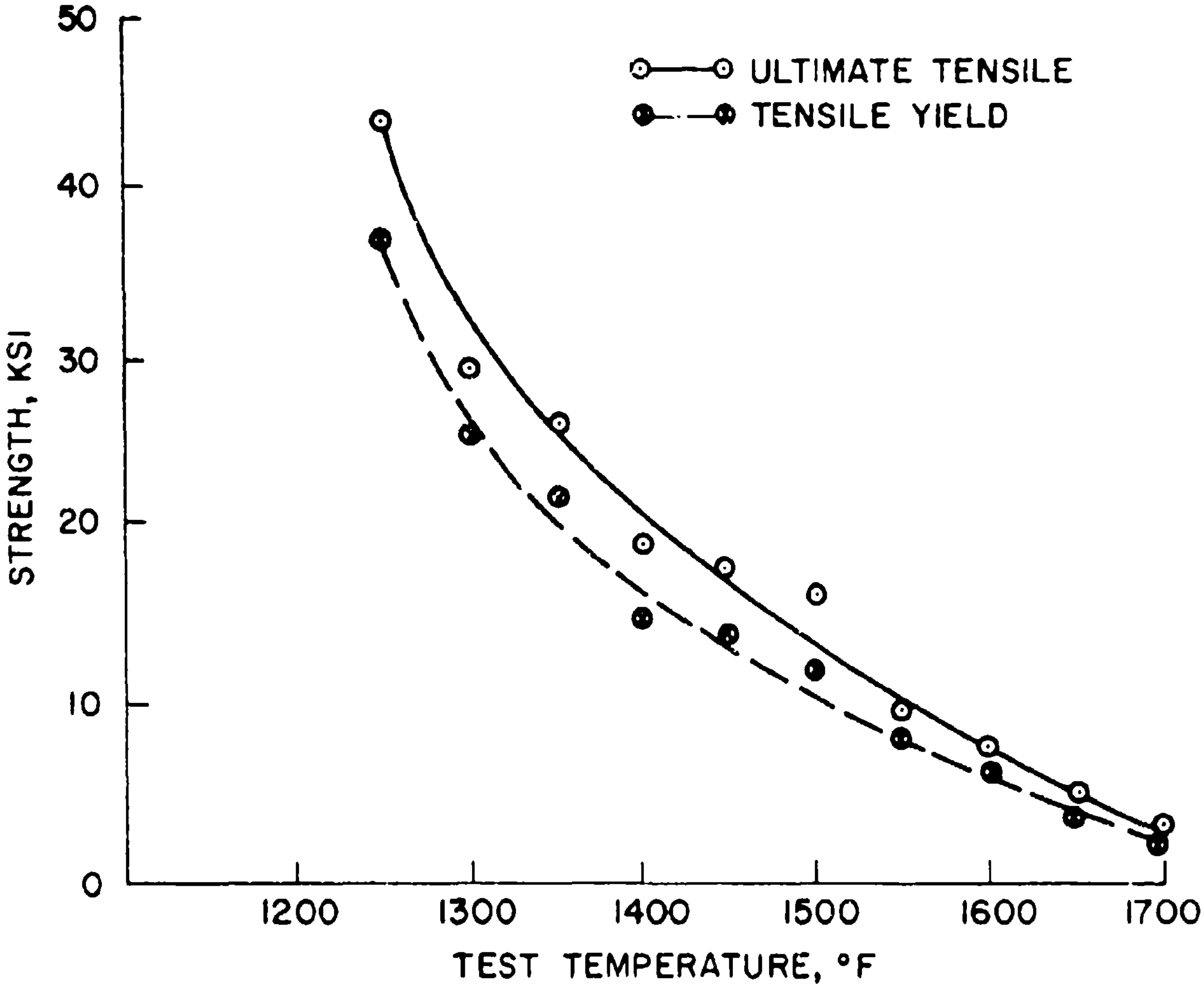
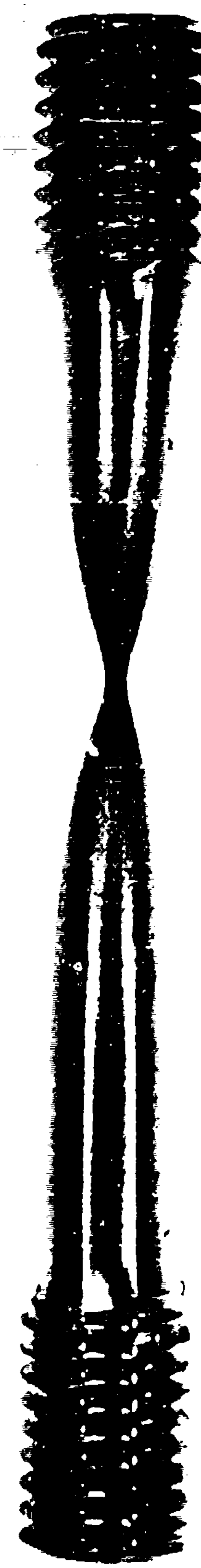


Figure 3
Tensile Strength/Temperature Relationship for Ti-6A1-4V, ELI

Item (a)
Tested at 1750° F



Item (b)
Tested at 1550° F

Figure 4
Tensile Specimens Tested at 1750° and 1550° F
(Approximately 2X Magnification)

The results of mechanical property tests on material from the as-received annealed plate and from the as-formed hemisphere are shown in table 3. Strength and ductility were considerably lower in material from the hemisphere than in the plate material before it was formed. The property most affected, tensile yield strength, was down 11 1/2% to 14 1/2% from the plate value. Charpy V-notch energies for the hemisphere material were approximately twice those of the plate material. The improved toughness of the formed material is desirable and the tensile yield strength is acceptable for a Ti-100 class alloy.

TABLE 3

MECHANICAL PROPERTIES OF ANNEALED, HOT-PRESS-FORMED, AND HEAT TREATED Ti-6Al-4V, ELI PLATE MATERIAL

	Tensile Yield Strength 0.2% Offset ksi	Compressive Yield Strength 0.2% Offset ksi	Ultimate Tensile Strength ksi	Elongation in 4D %	Reduction in Area %	Charpy V-Notch Energy, ft-lb(1)	
						+32° F	-80° F
Annealed Plate(2)							
Radial							
Surface	123.0	128.4	128.0	16.9	31.8	19.2	15.0
Mid-Thickness	120.8	125.7	126.5	15.0	26.2	20.5	16.0
Tangential							
Surface	125.0	133.0	129.7	15.2	30.9	16.0	12.8
Mid-Thickness	120.6	130.3	126.1	15.3	32.9	18.0	14.5
Press-Formed Hemisphere(2)							
Radial							
Surface	107.5	118.2	123.2	13.7	27.7	32.5	27.7
Mid-Thickness	106.1	118.2	123.1	13.7	29.0	32.0	26.1
Tangential							
Surface	106.9	119.3	122.8	12.3	26.6	30.8	25.4
Mid-Thickness	107.0	122.4	124.1	11.7	25.4	32.3	25.0
Heat Treated Plate (2, 3)							
1550° F, WQ; 900° F Age							
Surface	123.2	131.5	133.7	11.4	17.7	28.7	23.5
Mid-Thickness	119.5	133.5	129.5	12.5	21.0	27.0	23.5
1750° F, WQ; 900° F Age							
Surface	123.5	131.2	138.0	11.4	22.1	27.5	23.0
Mid-Thickness	121.0	128.5	134.5	9.4	20.6	29.5	24.5
1750°, SQ; 900° F Age							
Surface	120.1	132.0	135.2	11.1	17.0	25.5	22.7
Mid-Thickness	120.0	128.5	133.5	10.2	13.0	30.0	26.0
1750° F, 1 min delay, SQ; 900° F Age							
Surface	121.0	134.5	134.7	11.7	19.5	26.7	24.2
Mid-Thickness	119.5	128.5	133.0	10.9	17.0	30.0	27.0

(1) Average of three specimens at each location.

(2) Tensile and compressive values are averaged from six specimens; two at mid-thickness, four at surfaces.

(3) Four hours at solution treating temperature; 8 hours at aging temperature.

WQ - water quenched.

SQ - spray quenched.

Strength properties for the heat-treated plate material, shown in table 3, were comparable to those of the original annealed plate and considerably higher than those of the as-formed hemisphere. Ductility, however, was lowest of the three material conditions. Charpy V-notch energy values of the heat-treated material were significantly higher than those for the original plate but somewhat lower than the hemisphere values. Mechanical properties obtained were similar regardless of the heat treatment. Uniformity of properties through the 4-inch thickness was very good. One may, therefore, choose either water bath or water spray quenching and need not be overly concerned should there be a short delay between furnace and quenching, provided that material temperature does not drop below 1550° F.

CONCLUSIONS AND RECOMMENDATIONS

The temperature range for hot-press-forming, heavy-section Ti-6Al-4V, ELI grade alloy titanium is 1500° to 1750° F.

Hot-press forming of one piece alloy titanium hemispheres greater than 7 feet in diameter and 4 inches thick is not feasible with presently available equipment.

The tensile yield strength of this alloy was reduced 11 1/2% to 14 1/2% by hot-press forming. Heat treatment improved the tensile yield strength to a value comparable to the annealed plate.

A solution-treat (1750° F) and age (900° F) heat treatment may be used to obtain improved toughness with strength values similar to annealed plate in 4-inch-thick Ti-6Al-4V, ELI material. The potential for producing large, heavy-section elements of alloy titanium at the 120 ksi yield strength level has therefore been indicated.

Since previous work[2] indicated that the toughness of as-welded Ti-6Al-4V, ELI weld metal was not sufficient to ensure ductile fracture in thick sections, further work on heat-treated weldments would be required before consideration could be given to its use as a 120 ksi yield strength alloy for deep submersible welded-hull structures. In this connection, it would be desirable to establish the mechanical, dynamic tear, stress corrosion, and fatigue properties of this material in the welded and heat-treated condition. In addition, it would also be desirable to weld in an insert and heat treat the entire 7-foot-diameter, Ti-6Al-4V, ELI hemisphere, currently on hand at the laboratory, to 120 ksi yield strength in order to determine the amount of distortion that would result from this operation and the effect of heat treatment on weld toughness.

FUTURE WORK

No further fabrication development work has been scheduled for the 6Al-4V, ELI alloy. However, the additional work suggested herein should be undertaken if firm requirements develop for a deep submergence vehicle with a welded pressure hull that requires the use of a material with the high strength-to-weight ratio of 120 ksi yield strength alloy titanium.

TECHNICAL REFERENCES

1 - Lengenfelder, F. J., "Mechanical Properties of High-Strength, Heavy-Section Alloy Titanium Forgings," NAVSHIPRANDCEN Annapolis Rept 8-956 (Dec 1971)

2 - Lukens, W. E., "Properties of Ti-6Al-2Cb-1Ta-1.2Mo and Ti-6Al-4V (ELI) Plate Weldments," NAVSHIPRANDCEN Annapolis Rept 8-950 (23 Mar 1972)

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DOCUMENT CONTROL DATA - R & D

Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Ship Research and Development Center Annapolis Laboratory Annapolis, Maryland 21402	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Hot Forming, Heat Treating, and Mechanical Evaluation of 4-inch-thick Ti-6A1-4V, ELI Plate

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Research and Development, Evaluation, Phase

5. AUTHOR(S) (First name, middle initial, last name)

Frank J. Lengenfelder

6. REPORT DATE August 1972	7a. TOTAL NO OF PAGES 19	7b. NO OF REFS 4
8a. CONTRACT OR GRANT NO Task Area SF 54-541-005 b. PROJECT NO c. Task 11896 d. Work Unit 1-2822-101	9a. ORIGINATOR'S REPORT NUMBER(S) 28-269 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY NAVSHIPS (SHIPS 03422)

13. ABSTRACT

Elevated temperature tensile properties of the Ti-6A1-4V, ELI grade alloy were determined and a forming temperature range was selected. A 7-foot-diameter hemisphere was hot-press formed from a 4-inch-thick plate according to laboratory-developed parameters. Mechanical property tests were conducted on the plate material before and after hot forming and after heat treating of the formed material. Results of these tests showed a lower tensile yield strength after hot forming and restoration of this property after heat treatment. The results indicate that a tensile yield strength of 120,000 pounds per square inch can be obtained throughout the thickness of the formed hemisphere after appropriate heat treatment.

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KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Titanium Alloy						
Tensile properties						
Forming temperature						
Hot forming						

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